What is claimed is:

1. 1. A timing error estimation apparatus for multi-
2. carrier systems, comprising:
3. a timing offset compensator for receiving a current
4. symbol in a frequency domain after taking an *N*-
5. point Discrete Fourier Transform (DFT) and
6. compensating said current symbol for an effect of
7. timing offset with a timing offset prediction
8. value; and
9. a timing error estimator coupled to said timing offset
10. compensator to take a timing compensated version
11. of said current symbol on pilot subcarrier
12. locations, for calculating a timing error value
13. based on a function of a phase tracking value, a
14. channel response of each pilot subcarrier,
15. transmitted data on each pilot subcarrier, and
16. said timing compensated version of said current
17. symbol on said pilot subcarrier locations.

1. 2. The apparatus as recited in claim 1 wherein said
2. timing error value of said current symbol, $\tau_{\varepsilon,i}$, is defined
3. by:
4. $\tau_{\varepsilon,i} = \tau_{E,i} - \tau_{P,i}$
5. where
6. subscript *i* denotes a symbol index,
7. $\tau_{E,i}$ is a measure of timing offset of symbol *i*,
8. $\tau_{P,i}$ is said timing offset prediction value of symbol *i*,
9. and
10. $\tau_{\varepsilon,i}$ represents said timing error value of symbol *i*.

1   3. The apparatus as recited in claim 1 wherein said

2 timing error estimator calculates said timing error value by

3 the following function:

4 $$\tau_{\varepsilon,i} = -\frac{N}{2\pi} \frac{\text{Im}\left\{e^{-j\phi_{T,i}} \sum_{m=1}^{N_{SP}} p_m R'_{i,p_m} \left(H_{p_m} X_{i,p_m}\right)^*\right\}}{\sum_{m=1}^{N_{SP}} p_m^2 |H_{p_m}|^2}$$

5 where

6   superscript * denotes complex conjugation,

7        $\text{Im}\{\cdot\}$ denotes the imaginary part of a complex number,

8        $\phi_{T,i}$ denotes said phase tracking value of symbol i,

9   N_{SP} is the number of said pilot subcarriers,

10   p_m denotes a pilot subcarrier index, for $m = 1, 2, \ldots, N_{SP}$,

11   H_{p_m} denotes said channel responses of pilot subcarrier

12   p_m,

13   X_{i,p_m} denotes said transmitted data on pilot subcarrier

14   p_m of symbol i,

15   R'_{i,p_m} denotes said timing compensated version of the ith

16   symbol on pilot subcarrier location p_m, and

17       $\tau_{\varepsilon,i}$ denotes said timing error value of symbol i.

1   4. The apparatus as recited in claim 1 wherein said

2 timing offset compensator is employed to compensate the ith

3 symbol on pilot subcarrier location p_m using said timing

4 offset prediction value of the ith symbol and provides as

5 output said timing compensated version of the ith symbol on

6 pilot subcarrier location p_m.

1   5. A timing tracking apparatus for multi-carrier

2 systems, comprising:

3   a parameter table for storing a plurality of loop

4   parameters;

5   an *n*th-order tracking loop for computing a timing

6   offset prediction value for a next symbol based

7   on a timing error value of a current symbol, said

8   timing offset prediction value of said current

9   symbol and said loop parameters that are

10   retrieved from said parameter table for said

11   current symbol; and

12   a timing synchronizer for generating a shift amount of

13   a DFT window for said next symbol according to

14   said timing offset prediction value of said next

15   symbol, in which said DFT window shift amount is

16   equal to zero if said timing offset prediction

17   value of said next symbol is within a

18   predetermined range;

19   wherein said timing synchronizer applies said DFT

20   window shift amount to align the DFT window and

21   further starts an inhibit interval if said shift

22   amount is not equal to zero, and provides said

23   DFT window shift amount for further subtraction

24   from said timing offset prediction value upon

25   completion of said inhibit interval.

1   6. The apparatus as recited in claim 5 wherein said

2   timing synchronizer sets said DFT window shift amount to

3   zero for said next symbol during said inhibit interval,

4   except upon the start of said inhibit interval.

1   7. The apparatus as recited in claim 5 wherein said

2   *n*th-order tracking loop computes a timing offset tracking

3 value and a period offset tracking value for said current

4 symbol based on said loop parameters regarding said current

5 symbol, said period offset tracking value of a preceding

6 symbol, said timing offset prediction and said timing error

7 values of said current symbol, and yields said timing offset

8 prediction value for said next symbol by summing said timing

9 offset and said period offset tracking values of said

10 current symbol.

1   8. The apparatus as recited in claim 5 wherein said

2 nth-order tracking loop is a second-order tracking loop

3 modeled with a set of recursive equations, as follows:

4
$$\tau_{T,i} = \tau_{P,i} + \mu_{\tau,i}\tau_{\varepsilon,i}$$
$$v_{T,i} = v_{T,i-1} + \mu_{v,i}\tau_{\varepsilon,i}$$

5 and

6
$$\tau_{P,i+1} = \tau_{T,i} + v_{T,i}$$

7 where

8   subscript i denotes a symbol index,

9      $\tau_{T,i}$ and $v_{T,i}$ denote a timing and period offset tracking

10   value of symbol i, respectively,

11      $\mu_{\tau,i}$ and $\mu_{v,i}$ denote said loop parameters of the ith

12   symbol for $\tau_{T,i}$ and $v_{T,i}$, respectively,

13      $\tau_{P,i}$ denotes said timing offset prediction value of the

14   ith symbol,

15      $\tau_{P,i+1}$ is said timing offset prediction value of symbol

16          $i+1$,

17      $v_{T,i-1}$ is said period offset tracking value of symbol $i-1$,

18 and $\tau_{\varepsilon,i}$, said timing error value of the ith symbol, is given

19 by:

20
$$\tau_{\varepsilon,i} = \tau_{E,i} - \tau_{P,i}$$

21 where $\tau_{E,i}$ is a measure of timing offset of the ith symbol.

1   9. The apparatus as recited in claim 8 wherein said
2 second-order tracking loop receives as input a frequency
3 offset estimate and calculates an initial value for said
4 period offset tracking value as follows:

5       $$v_{T,i} = -N' \cdot \frac{\hat{f}_d}{f_c} , \quad i = -1$$

6 and

7       $$N' = \frac{T'}{T_s}$$

8 where

9       $\hat{f}_d$ denotes said frequency offset estimate,

10   f_c denotes a nominal carrier frequency,

11   T' denotes a symbol interval,

12   T_s denotes a sampling period,

13      $v_{T,i}$ denotes said period offset tracking value of symbol

14   i, and

15      $v_{T,-1}$ denotes said initial value for $v_{T,i}$.

1   10. A timing offset compensation apparatus for multi-
2 carrier systems, comprising:
3   a timing offset compensator for receiving a current
4   symbol in a frequency domain after taking an N-
5   point Discrete Fourier Transform (DFT) and
6   compensating said current symbol for an effect of
7   timing offset with a timing offset prediction
8   value;
9   a timing error estimator for taking a timing
10   compensated version of said current symbol on
11   pilot subcarrier locations and calculating a

12   timing error value for said current symbol based

13   on a function of a phase tracking value, a

14   channel response of each pilot subcarrier,

15   transmitted data on each pilot subcarrier, and

16   said timing compensated version of said current

17   symbol on said pilot subcarrier locations; and

18   a timing tracking unit for receiving said timing error

19   value of said current symbol to generate said

20   timing offset prediction value and a shift amount

21   of a DFT window for a next symbol.

1   11. The apparatus as recited in claim 10 wherein said

2   timing error value of said current symbol, $\tau_{\varepsilon,i}$, is defined

3   by:

4        $$\tau_{\varepsilon,i} = \tau_{E,i} - \tau_{P,i}$$

5   where

6   subscript i denotes a symbol index,

7        $\tau_{E,i}$ is a measure of timing offset of symbol i,

8        $\tau_{P,i}$ is said timing offset prediction value of symbol i,

9   and

10        $\tau_{\varepsilon,i}$ represents said timing error value of symbol i.

1   12. The apparatus as recited in claim 10 wherein said

2   timing error estimator calculates said timing error value by

3   the following function:

4        $$\tau_{\varepsilon,i} = -\frac{N}{2\pi} \frac{\text{Im}\left\{ e^{-j\phi_{T,i}} \sum_{m=1}^{N_{SP}} p_m R'_{i,p_m} \left(H_{p_m} X_{i,p_m} \right)^* \right\}}{\sum_{m=1}^{N_{SP}} p_m^2 \left| H_{p_m} \right|^2}$$

5   where

6   superscript $*$ denotes complex conjugation,

7   $\mathrm{Im}\{\cdot\}$ denotes the imaginary part of a complex number,

8   $\phi_{T,i}$ denotes said phase tracking value of symbol i,

9   N_{SP} is the number of said pilot subcarriers,

10 p_m denotes a pilot subcarrier index, *for* $m = 1, 2, ..., N_{SP}$,

11 H_{p_m} denotes said channel responses of pilot subcarrier

12   p_m,

13 X_{i,p_m} denotes said transmitted data on pilot subcarrier

14   p_m of symbol i,

15 R'_{i,p_m} denotes said timing compensated version of the ith

16   symbol on pilot subcarrier location p_m, and

17 $\tau_{\varepsilon,i}$ denotes said timing error value of symbol i.

1   13. The apparatus as recited in claim 10 wherein said

2   timing offset compensator is employed to compensate the ith

3   symbol using said timing offset prediction value of the ith

4   symbol and provides as output said timing compensated

5   version of the ith symbol, $R'_{i,k}$, where subscript k denotes a

6   subcarrier index.

1   14. The apparatus as recited in claim 10 wherein said

2   timing tracking unit comprises an nth-order tracking loop to

3   generate said timing offset prediction value for said next

4   symbol by computing a timing offset tracking value and a

5   period offset tracking value of said current symbol.

1   15. The apparatus as recited in claim 14 wherein said

2   timing tracking unit further comprises a timing synchronizer

3   to receive said timing offset prediction value of said next

4   symbol from said nth-order tracking loop, generate said DFT

5   window shift amount for said next symbol, and further start

6   an inhibit interval if said shift amount is not equal to

7 zero, in which said DFT window shift amount is applied to

8 align the DFT window and is provided for further subtraction

9 from said timing offset prediction value upon completion of

10 said inhibit interval.

1 16. The apparatus as recited in claim 10 wherein said

2 timing tracking unit comprises:

3 a parameter table for storing a plurality of loop

4 parameters;

5 an nth-order tracking loop for computing said timing

6 offset prediction value for said next symbol

7 based on said timing error value of said current

8 symbol, said timing offset prediction value of

9 said current symbol and said loop parameters that

10 are retrieved from said parameter table for said

11 current symbol; and

12 a timing synchronizer for generating said DFT window

13 shift amount for said next symbol according to

14 said timing offset prediction value of said next

15 symbol, in which said DFT window shift amount is

16 equal to zero if said timing offset prediction

17 value of said next symbol is within a

18 predetermined range;

19 wherein said timing synchronizer applies said DFT

20 window shift amount to align the DFT window and

21 further starts an inhibit interval if said shift

22 amount is not equal to zero, and provides said

23 DFT window shift amount for further subtraction

24 from said timing offset prediction value upon

25 completion of said inhibit interval.

1   17. The apparatus as recited in claim 16 wherein said

2   timing synchronizer sets said DFT window shift amount to

3   zero for said next symbol during said inhibit interval,

4   except upon the start of said inhibit interval.

1   18. The apparatus as recited in claim 16 wherein said

2   nth-order tracking loop is a second-order tracking loop

3   modeled with a set of recursive equations, as follows:

4
$$\tau_{T,i} = \tau_{P,i} + \mu_{\tau,i}\tau_{\varepsilon,i}$$
$$v_{T,i} = v_{T,i-1} + \mu_{v,i}\tau_{\varepsilon,i}$$

5   and

6
$$\tau_{P,i+1} = \tau_{T,i} + v_{T,i}$$

7   where

8   subscript i denotes a symbol index,

9         $\tau_{T,i}$ and $v_{T,i}$ denote a timing and period offset tracking

10   value of symbol i, respectively,

11         $\mu_{\tau,i}$ and $\mu_{v,i}$ denote said loop parameters of the ith

12   symbol for $\tau_{T,i}$ and $v_{T,i}$, respectively,

13         $\tau_{P,i}$ denotes said timing offset prediction value of the

14   ith symbol,

15         $\tau_{P,i+1}$ is said timing offset prediction value of symbol

16   i+1,

17         $v_{T,i-1}$ is said period offset tracking value of symbol i–1,

18   and $\tau_{\varepsilon,i}$, said timing error value of the ith symbol, is given

19   by:

20
$$\tau_{\varepsilon,i} = \tau_{E,i} - \tau_{P,i}$$

21   where $\tau_{E,i}$ is a measure of timing offset of the ith symbol.

1   19. The apparatus as recited in claim 18 wherein said

2   second-order tracking loop receives as input a frequency

3 offset estimate and calculates an initial value for said

4 period offset tracking value as follows:

5 $$v_{T,i} = -N' \cdot \frac{\hat{f}_d}{f_c} \, , \quad i = -1$$

6 and

7 $$N' = \frac{T'}{T_s}$$

8 where

9 $\hat{f}_d$ denotes said frequency offset estimate,

10 f_c denotes a nominal carrier frequency,

11 T' denotes a symbol interval,

12 T_s denotes a sampling period,

13 $v_{T,i}$ denotes said period offset tracking value of symbol

14 i, and

15 $v_{T,-1}$ denotes said initial value for $v_{T,i}$.

1   20. The apparatus as recited in claim 16 wherein said

2 timing tracking unit further comprises a flip-flop that

3 receives as input said timing offset prediction value of

4 said next symbol and provides as output said timing offset

5 prediction value for said current symbol.